METHOD AND APPARATUS FOR DETERMINING A VEHICLE GEAR RATIO

FIELD OF THE INVENTION

[0001] The invention relates to work vehicles such as agricultural combines. More particularly, it relates to work vehicles having gearboxes without a gear select sensor. Even more particularly, it relates to such vehicles having electronic control systems configured to determine gear ratios.

BACKGROUND OF THE INVENTION

[0002] Work vehicles such as agricultural combines monitor a variety of drive parameters. They have a variety of sensors responsive to pressures, speeds and positions of the various components that comprise the drive system.

[0003] For example, a sensor may directly indicate the gear ratio or gear range of a gearbox in the drive system. Other sensors may measure different parameters, such as hydraulic pressure, rotational speed, and other parameters.

[0004] In some vehicles, system parameters such as gear ratios may not be sensed directly, but may be determined by combining sensor data and knowledge of the mathematical system model to calculate or otherwise determine these system parameters.

[0005] An example of such a system is disclosed in the assignee's co-pending US Pat. App. Ser. No. 10/167,310 ("310 application") filed June 11, 2002, for a "COMBINE HAVING A SYSTEM ESTIMATOR TO AUTOMATICALLY ESTIMATE AND DYNAMICALLY CHANGE A TARGET CONTROL PARAMETER IN A CONTROL ALGORITHM". In this application, a gear ratio is determined by an electronic controller

coupled to a motor speed sensor and a rotor speed sensor. By monitoring a gearbox input speed (the motor) and a gearbox output speed (the rotor) the system of the '310 application is able to determine the selected gearbox gear ratio indirectly.

[0006] The system and method of the '310 application is not without limitations. It is predicated on accurately calculating the speed range during an initial 1.3 second hydrostatic rotor acceleration phase. It also requires correct operation of the motor speed sensor. Should the motor sensor fail, the system may not be able to accurately determine the gear ratio.

[0007] It is an object of this invention to provide an improved system and method for determining the gear ratio of a gearbox.

[0008] It is also an object of this invention to provide for a redundant method to determine gearbox ratios.

SUMMARY OF THE INVENTION

[0009] In accordance with a first aspect of the invention, a combine is provided that includes a chassis on which an engine and a drive system are mounted. An electronic control system with at least one sensor monitors a physical parameter of the drive system, applies that measured parameter value to a mathematical model of the drive system, which provides another physical parameter of the drive system.

[0010] In accordance with a second aspect of the invention, a system estimator for a work vehicle is provided, the work vehicle having a dynamic system that is capable of being modeled in terms of at least one measurable physical parameter and a second physical parameter said second parameter being indicative of an operating condition of the dynamic system, the system estimator comprising an electronic controller including a digital microprocessor and an electronic digital memory, the memory including a sequence of preprogrammed instructions including a model of the dynamic system expressed at least in terms of the at least one measurable parameter; and at least one sensor coupled to the dynamic system and the electronic controller to generate a first signal indicative of the at least one measurable parameter and to provide the first signal to the electronic controller, wherein the electronic controller is configured to receive the

first signal, apply it to the model of the dynamic system and estimate a value of the second parameter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] **FIGURE 1** is a side schematic view of an agricultural combine having a gearbox with gear ratios determined by the present invention.

[0012] **FIGURE 2** is an electronic, hydraulic and mechanical schematic diagram of the drive system of the combine of **FIGURE 1**.

[0013] **FIGURE 3** is a timing diagram of the rotor acceleration process showing the rotor speed, clutch engagement signals and pump command signals for a time interval i= 0 to i>462.

[0014] **FIGURE 4 is** a flow chart of a process performed by controller **234** of sequentially calculating gear ratios of a gear box over a first predetermined interval.

[0015] **FIGURE 5** is a flow chart of the process of selecting between the gear ratios calculated in the process of **FIG. 4** performed by controller **234**.

[0016] **FIGURE 6** is a flow chart of a second gear ratio calculation process performed by controller **234** whenever the process of **FIGURES 4** and **5** fails.

DETAILED DESCRIPTION OF THE INVENTION

[0017] Referring to **FIGURE 1**, a work vehicle is illustrated, here shown as an agricultural combine **100**. The work vehicle has a chassis **102** on which an engine **104** is mounted. A drive system **106** is coupled to and driven by engine **104** to rotate rotor **118**. An electronic control system **108** is coupled to the engine and the drive system to monitor various sensors, to control the engine and to control the drive system.

[0018] The engine **104** is preferably an internal combustion engine, such as a multi-cylinder gasoline or diesel engine.

[0019] The drive system **106** includes a hydraulic pump **110** that is coupled to and driven by the engine, a hydraulic motor **112** that is fluidly coupled to and driven by pump **110**, a gear train coupling engine **104** to the pump, a gear train coupling engine **104** to a planetary gear arrangement, the planetary gear arrangement **114** (**FIG. 2**) itself, and a

gearbox **116** (**FIG. 2**) that drives the combine rotor **118**.

[0020] Rotor **118** rotates with respect to chassis **102** and threshes agricultural material, such as corn stalks. A header **120** is attached to the front of the combine to cut and gather the agricultural material from the field and direct it into the rotor, via the feeder **124**, which receives and threshes it.

[0021] A plurality of wheels **122** are coupled to the chassis to engage the ground and support the combine as it travels over the ground. One or more motors (not shown) may be coupled to the wheels to drive the wheels in rotation, thereby driving the combine over the ground.

[0022] **FIGURE 2** illustrates construction details of the work vehicle (and particularly the drive system **106**) in a schematic form. Engine **104** has an output shaft **200** to which spur gear **202** is fixed. Gear **202** drives spur gear **204**. Spur gear **204** is fixed to shaft **206**, which is the input shaft to hydraulic pump **110**.

[0023] Hydraulic pump **110** is a variable displacement pump in which the specific output can be varied under electrical control. In particular, pump **110** has internal actuators to vary the displacement of the pump in response to an electrical signal. Controller **234** applies the signal to pump **110** over electrical control lines **209**.

[0024] Gear **202** also meshes with and drives spur gear **210**, which is coupled to and drives the auger and header (not shown). Spur gear **210**, in turn, meshes with and drives spur gear **212**. Spur gear **212**, in turn, is coupled to and drives the input shaft of engine-to-ring clutch **214**.

[0025] Engine-to-ring clutch **214** is a hydraulically actuated multi-plate clutch that couples gear **212** (and hence engine **104**) to ring gear **216** of planetary gear arrangement **114**. When clutch **214** is engaged, engine **104** is coupled to and drives ring gear **216**. When clutch **214** is disengaged, engine **104** is disconnected from ring gear **216**.

[0026] A second clutch **220** (a ring-to-frame clutch) is coupled to and between ring gear **216** and the frame or chassis **102** (indicated by the ground symbol) to fix the ring gear with respect to the chassis or frame of the vehicle. When clutch **220** is engaged, ring gear **216** is fixed and cannot rotate.

[0027] Pump **110** is hydraulically connected to motor **112** by hydraulic conduits **222**. These conduits conduct fluid to and from motor **112** to form a closed loop hydraulic (hydrostatic) drive circuit.

[0028] Motor **112** is coupled to and drives sun gear **224** of planetary gear arrangement **114**. Sun gear **224** drives planet gears **226**, which drive planetary gear carrier **228**.

[0029] Gearbox **116** is a multi-speed gearbox having a neutral and three manually selectable gear ratios with an input shaft **230** and an output shaft coupled to rotor **118**.

[0030] Input shaft **230** of gearbox **116** is fixed to and rotates together with planetary gear carrier **228**. The output shaft of multi-speed gearbox **116** is coupled to and drives rotor **118**.

[0031] It should be clear that power from engine **104** to rotor **118** can follow one or both of two parallel paths. The first path is from engine **104**, through the gearing, through clutch **214**, through ring gear 216, through planet gears **226** into shaft **230**. The second parallel path is from engine **104**, through pump **110**, through motor **112**, through sun gear **224**, through the planet gears **226** and into shaft **230**.

[0032] The normal mode of operation, however, is one in which power through both paths is provided to the rotor. Engine **104** operates most efficiently at a set and predetermined rpm, yet the rotor cannot be operated at a set, predetermined speed, but must be variable over some range or ranges of speed to harvest the several types of crops it is intended and designed to do.

[0033] To provide this variable rotor speed, two parallel power paths are provided. The planetary gear arrangement permits power through both paths to be applied to the rotor. The motor drives the sun gear, the engine drives the ring gear, and the planetary gear carrier receives power from both and applies that combined power to the rotor through gearbox **116**.

<u>ELECTRONICS</u>

[0034] The electronic control system **108**, including three digital electronic controllers and their associated sensors, controls the operation of the foregoing machine elements.

[0035] System **108** includes a first digital electronic controller **234**, a second digital electronic controller **236** and a third digital electronic controller **238** that are coupled together over a communications network, here shown as a CAN bus **240** in accordance with the SAE J1939 communications standard.

[0036] Each controller **234**, **236**, and **238** are similarly constructed, and include a microprocessor **242**, a read-only memory (ROM) **244**, a random access memory (RAM) **246** and an input/output (I/O) circuit **248**. The ROM stores a control program that controls the operation of the controller. The RAM is temporary storage space for numeric values used in computation, and the I/O circuit handles external communications including communications with the sensors and the other controllers on the CAN bus **240**. Each of these circuits is connected using a data/address/control bus of standard design, which is not shown.

[0037] The first digital controller **234** is connected to two speed sensors, a rotor speed sensor **252**, and a motor speed sensor **254**. These sensors are respectively coupled to rotor **118** and motor **112** to sense the rotational speeds of these devices and transmit a signal indicative of those speeds to the first digital controller **234**.

[0038] The speed sensors in the present system preferably generate a series or stream of pulses as the rotor and motor turn.

[0039] Common sensor arrangements that generate such pulse sequences include conditioned alternator signals, Hall Effect devices, and inductive pickups that sense the passage of slotted disks or gear teeth mounted on the shafts of the engine, rotor and motor, for example.

[0040] The first digital controller **234** is also connected to and controls three other devices: pump **110**, engine-to-ring clutch **214** and ring-to-frame clutch **220**.

[0041] Controller **234** generates and transmits a signal indicative of a desired specific displacement to pump **110**. Pump **110** responsively changes its specific displacement to match the signal. In a similar fashion, controller **234** generates and transmits a clutch-engaging or clutch-disengaging signal to electrical solenoid valves (not shown) that conduct hydraulic fluid to and from the two clutches **214** and **220**. The clutches responsively engage and disengage.

[0042] The I/O circuit of second digital controller **236** is connected to an engine speed sensor **256** and to operator input device **258**. Engine speed sensor **256** generates a signal indicative of the engine speed. The operator input device is preferably a switch responsive to operator manipulation that generates two separate signals, an "increase speed" signal and a "decrease speed" signal. Controller **236** is also connected to controller **234** and controller **238** via the CAN bus **240**.

[0043] The third and final controller, controller **238**, is a display controller. It is constructed the same as controller **234** and **236**, but is dedicated to displaying data generated by the operator or the other controllers. This capability is provided by its own internal control program stored in its ROM memory. It also includes a display device such as an LCD or electroluminescent display.

PROGRAMMING

[0044] Controllers **234**, **236**, and **238** include internal digital control programs that control their operation. These programs are stored in the ROM memory of each controller. The programmed operation of each controller is discussed below.

[0045] During normal operation, controller **238** displays several data indicative of the vehicle's status. The first of these, the rotor speed, indicates the speed of the rotor. Controller **234** generates the rotor speed data from the rotor speed signal transmitted to controller **234** from rotor speed sensor **252**. Controller **234** periodically calculates the rotor speed from the rotor speed signal and places this information on the CAN bus. The rotor speed is preferably calculated and placed on the CAN bus in regular intervals.

[0046] Controller **238** is programmed to receive this rotor speed data over the CAN bus, and to translate them into display signals to drive its integral display. It applies the

display signals to the display, thereby generating decimal digits on the display that represent the rotor speed. The display indicates the rotor speed as a sequence of decimal digits expressed in revolutions per minute.

[0047] Controller **238** also displays the current range of rotor speed. This range is displayed in the form of an upper and a lower limiting rotor speed. These limits are typically generated by controller **234** and transmitted in regular intervals over the CAN bus to controller **238**.

[0048] Controller **238** receives these speed range signals, translates them into display signals to drive its integral display, and applies the signals to the display thereby generating decimal digits on the display that represent the upper and lower rotor speed limit values. These values are preferably expressed in revolutions per minute.

[0049] Controller **236** receives the increase-rotor-speed and the decrease-rotor-speed signals (also known as operator speed requests or commands) from operator input device **258** when the operator manipulates the operator input device. Controller **236** transmits these operator requests on the CAN bus. Controller **234** receives these operator requests and attempts to raise or lower the rotor speed accordingly,

[0050] Controller **234** controls the rotor speed by changing the specific displacement of pump **110**. Controller **234** is programmed to execute a conventional PID control loop that uses the commanded rotor speed (from the operator input device), the actual rotor speed (provided by the rotor speed sensor) as inputs, and generates a signal that is applied to pump **110** as the output. The difference between the actual rotor speed and the commanded rotor speed is the error signal that is minimized by the PID control loop.

[0051] Controller **234** changes the commanded rotor speed based at least on two things: first, a command by the operator using the operator input device to either raise or lower the current commanded speed, and second, controller's (234) determination that the rotor can indeed be driven at the new speed requested by the operator. If both conditions are met, controller **234** changes the commanded rotor speed according to the PID design.

[0052] Controller **234** also determines whether the motor or the engine (or both) drives the rotor by selectively engaging and disengaging the engine-to-ring clutch **214**

and the ring-to-frame clutch **220**. In the discussion below, controller **234** transmits engagement and disengagement signals to the hydraulic valve (not shown) that controls the engine-to-ring clutch **214**, causing it to become engaged (thereby connecting the engine to the ring gear) and disengaged (breaking the engine-to-ring gear connection). Controller **234** also transmits engagement and disengagement signals to the hydraulic valve controlling the ring-to-frame clutch, causing it to engage (locking the ring with respect to the chassis or frame) and to disengage (releasing the ring).

[0053] In the normal harvesting mode, discussed herein, both the motor and the engine drive the rotor. In this mode, called the hydro-mechanical mode, the engine runs at a relatively constant speed of 2150 rpm which, through the gearing and engine-to-ring clutch **214** connecting the engine to the ring gear, causes the ring gear to rotate at 2188 rpm.

[0054] The motor **112** is designed to be bi-directionally driven by pump **110** over a range of speeds from –4077 rpm to +3114 rpm. Given the gear ratios of the planetary gear arrangement, these speeds cause planetary gear carrier **228** to rotate at speeds ranging from 1144 to 2342 rpm.

[0055] In the normal (or hydro-mechanical) mode the rotor can be driven at an infinite number of speeds in either direction since the motor has a limited range of operating speeds, the engine operates at a relatively fixed speed, and gearbox **116** has a predetermined set of gear ratios. By "gear ratio" we mean the ratio of gearbox input shaft speed versus gearbox output shaft speed. Given these constraints, for any selected gear ratio of gearbox **116**, there is an associated and predetermined range of permissible rotor speeds. These speeds are expressed as a rotor speed upper limit and a rotor speed lower limit.

[0056] The input shaft **230** of gearbox **116** is connected to and driven by the planetary gear carrier **228**. The gearbox has a neutral and three different selectable gear ratios -- ratios of gearbox input shaft to output shaft speeds. These gear ratios are selectable by manual operator manipulation of a conventional gearshift lever **260**.

[0057] Given the gear ratio of the planetary gear arrangement, input shaft **230** of gearbox **116** rotates at speeds of between 1144 and 2342 rpm; at 1144 rpm, the motor

is rotating at –4077 rpm. At 2342 rpm, the motor is rotating at 3114 rpm.

[0058] The highest gearbox gear ratio rotates the output shaft of the gearbox (and the rotor to which it is coupled) at a speed of between 589 and 1206 rpm. For the middle gear ratio, this speed is between 391 and 800 rpm. For the lowest gear ratio, this speed is between 222 and 454 rpm. The output shaft speed varies with the motor speed.

[0059] When the motor rotates at –4077 rpm (and, again, assuming a fixed engine speed of 2150 rpm), the rotor rotates at 589, 391, or 222 rpm, depending upon the gearbox **116** gear ratio. When the motor rotates at +3114 rpm, the rotor rotates at 1206, 800, or 454 rpm, depending upon the gear ratio.

[0060] Controller **234** achieves intermediate speeds within these rotor speed ranges by varying the motor speed from –4077 to +3114 rpm. Controller **234** does this by changing the displacement of pump **110** according to the PID control design.

[0061] The operator is interested in controlling the rotor speed, since the rotor speed determines the rate at which the combine performs its work. It is for this reason that controller **234** is configured to transmit the rotor speed on the CAN bus **240** to controller **238** to be displayed.

[0062] The operator can select any rotor speed, however, but the ranges of permissible rotor speeds are limited based upon the selected gear ratio of gearbox **116**. Each gearbox gear ratio has its own associated range of rotor speeds. As a result, the operator is also interested in knowing the range of rotor speeds within which he can select the commanded rotor speed. It is for this reason that controller **234** transmits the rotor speed range (which depend upon the currently selected gearbox gear ratio) on the CAN bus to controller **238** to be displayed, since controller 234 defines the upper and lower permissible rotor speeds.

<u>DYNAMIC SYSTEM MODEL</u>

[0063] The drive train system is modeled as a dynamic system having three inputs and a single output. The inputs are (a) motor speed, (b) rotor speed, and (c) engine speed. The physical output is the gear ratio. The model below, expressed as a series

of equations that represent the dynamic response of the system, is applicable to the drive system when the engine-to-ring clutch **214** is engaged, and the ring-to-frame clutch is disengaged.

[0064] The relationship between these measurable inputs and outputs are expressed in the following equations 1-3. There are three equations since there are three different operator selectable gear ratios, representing the dynamic response to the drive system when the engine-to-ring clutch **214** is engaged and the ring-to-frame clutch is disengaged.

$$RS = K1*(KX*KZ*ES + KY*MS) \qquad \text{Eqn. 1}$$

$$RS = K2*(KX*KZ*ES + KY*MS) \qquad \text{Eqn. 2}$$

$$RS = K3*(KX*KZ*ES + KY*MS) \qquad \text{Eqn. 3}$$

[0065] RS is the rotor speed. ES is the engine speed. MS is the motor speed. K1, K2 and K3 are constants corresponding to the high, medium and low gear ratios, respectively, provided by gearbox **116**. KX and KY are constants corresponding to the mathematical model of the planetary gear arrangement. KZ is a constant corresponding to the model of the gear train between engine **104** and the ring gear.

[0066] These three equations can be summarized as follows:

$$RS = KGR*(KX*KZ*ES + KY*MS) \qquad \text{Eqn. 3a}$$

where KGR is the gear ratio of the gearbox. KGR will equal either K1, K2 or K3 depending upon the gearbox's selected gear ratio.

[0067] Equations 1-3 are one expression of the mathematical dynamic system model of the drive system expressed in a rather condensed form. The details of the model can be seen in the sub-equations that model each sub-equation of the drive system, which are described below.

[0068] The engine to ring gear drive train model is as follows:

$$RGS = ES * KZ \qquad \text{Eqn. 4}$$

where RGS is ring gear speed, ES is engine speed, and KZ is constant equal (in this embodiment) to 2188 rpm/2150 rpm or 1.017. This is true when the engine-to-ring clutch **214** is engaged and the ring-to-frame clutch is disengaged. However, when the engine-to-ring clutch **214** is disengaged and the ring-to-frame clutch is engaged, the engine is no longer coupled to the ring gear and the two can vary.

The model that represents this mode of operation (the motor alone driving the rotor) is a variation on the model expressed in the existing equations herein and is also stored in controller **234** to permit gear ratio to be estimated when the motor alone drives the rotor.

[0069] This variant of the existing equations (and hence the variant mathematical model) is provided by setting the engine speed (ES) and the ring gear speed (RGS) equal to zero in the equations. If these two substitutions are made in the equations herein, the modified equations represent a variant model of the system as it operates when the engine is disengaged from the rotor and the rotor is driven only by the motor.

[0070] Thus, controller **234** also includes a variant mathematical model of the drive system that it uses to estimate gear ratio for the case in which the ring is stopped and locked to the chassis via the ring-to-frame clutch and only the motor is driving the rotor.

[0071] The motor to planetary gear arrangement model is as follows:

$$MS = SGS \qquad \text{Eqn. 5}$$

where MS is motor speed and SGS is sun gear speed. This relation indicates that the motor and the sun gear turn at the same speed, since the sun gear is fixed to the motor shaft.

[0072] The planetary gear arrangement model is as follows:

$$PSS = KX*RGS + KY*SGS \qquad \text{Eqn. 6}$$

PSS is the planetary spider speed. RGS is the ring gear speed. SGS is the sun gear

speed. KX and KY are constants defined by the geometry of the planetary gear arrangement – by the number of teeth on the planetary gears. KX in this embodiment is 5/6. KY in this embodiment is 1/6.

[0073] The planetary to gearbox model is as follows:

$$GIS = PSS \qquad \text{Eqn. 7}$$

GIS is the gearbox input shaft speed. PSS is the planetary spider speed. This is true since the gearbox input shaft is fixed to the planetary gear spider.

[0074] The gearbox to rotor model is as follows:

$$RS = K1*GIS \qquad \text{Eqn. 8}$$

$$RS = K2*GIS \qquad \text{Eqn. 9}$$

$$RS = K3*GIS \qquad \text{Eqn. 10}$$

RS is rotor speed. K1, K2, and K3 are three constants corresponding to the high, medium, and low gear ratios of the gearbox **116** and equal to 0.51, 0.34 and 0.19, respectively. There are three equations since there are three different selectable gear ratios in gearbox **116**.

[0075] The foregoing equations 4-10 are reduced to equations 1-3, which are programmed into the electronic memory of controller **234**. They are preferably expressed as infinitesimals, differentials, or in tabular form for quick calculation during operation of controller **234**. While this is the preferred system model of the present embodiment, it should be obvious that other equations can be added to accommodate and represent a variety of other interactions as necessary. This would result in more complex drive system models and hence more calculations by controller **234**, but would have the advantage of more closely modeling the drive system.

<u>ESTIMATION OF GEAR RATIO</u>

[0076] Controller **234** must know or otherwise determine the gear ratio of gearbox

116 in order to perform various required functions, including displaying rotor speed limits, calculating alarm limits and the like. The discussion below explains how the gear ratios are estimated.

[0077] In order to determine the appropriate rotor speed limits to use, the gear ratio could be directly determined if any controller in the system was coupled to a gearbox sensor to indicate the gear ratio directly, such as by sensing the orientation of the gears within gearbox **116**, or the position of the gearshift lever **260** of gearbox **116**.

[0078] This would, however, require the use of an additional sensor to detect those physical parameters. The present system avoids the requirement of a separate gearbox **116** sensor by estimating the gear ratio using either (a) the rotor speed sensor and the engine speed sensor, or (b) the motor speed sensor and the rotor speed sensor.

[0079] Controller **234** first attempts to determine gearbox 116 gear ratio based upon the motor speed and the rotor speed. If this attempt fails, controller **234** again attempts to determine the gear ratio based upon the engine speed and the rotor speed.

[0080] These attempts to determine gear ratio happen at specific times while the operator initially starts and accelerates rotor 118 to full speed.

[0081] Before time t=0 (**FIG. 3**), the rotor and motor are stopped and the engine is running, with the ring-to-frame clutch engaged, which locks the ring gear with respect to the frame of the vehicle. Controller **234** awaits an operator command to spin the rotor.

[0082] At time t=0, the operator initiates threshing using the operator input device. In response, controller **234** signals the pump over signal lines **209** to change its displacement and the corresponding motor speed. This signal is shown in trace **300**, which represents the pump command that controller **234** applies to the pump.

[0083] Controller **234** gradually increases the pump command from time t=70 to time t=150 as shown in trace **300**. Rotor speed trace **306** shows that the rotor speed begins climbing as it is driven by the motor, which in turn is driven by hydraulic fluid from the pump 110.

[0084] At time t=150, the controller **234** applies the maximum signal to the pump and the motor **112** has responsively accelerated to its highest forward speed. Rotor **118**

responsively spins at its maximum speed in hydrostatic (e.g. motor only) drive mode.

[0085] At time t=200, after the rotor **118** has been spinning at a constant speed for 500 milliseconds, the controller **234** begins to speed up the rotor **118** again by coupling the engine with its direct mechanical drive to the rotor **118**. To do this, controller **234** disengages the ring-to-frame clutch, permitting the ring gear to spin freely. At the same time, controller **234** rapidly reverses the direction and speed of rotation of the motor **112**. This is shown by the sudden and extreme reversal in the pump command (trace 300) that controller **234** applies to the pump.

[0086] At time t= 240, the rotor **118** is coasting, the motor **112** is starting to spin in the opposite direction, and the ring gear is accelerating to match the speed of the engine. The ring gear speed and the engine speed are approaching one another. Controller **234** starts engaging the engine-to-ring clutch **214** (trace **302**) by applying an initial signal (see plateau **308**) to the engine-to-ring clutch **214**. This signal is calculated to rapidly take up all slack in the engine-to-ring clutch **214** and to bring the clutch to a point of near-engagement.

[0087] At time t= 270, the engine-to-ring clutch **214** begins to engage and the rotor **118** is again accelerating. To avoid a too-sudden engagement and the attendant shock loads, controller **234** reduces the engine-to-ring clutch **214** signal to a lower level **310** that will provide a more gradual and cushioned engagement.

[0088] At time t=375, the rotor **118** has accelerated to nearly a constant speed and the engine-to-ring clutch **214** slippage has dropped. The speeds of the engine and the ring gear are nearly matched. Controller **234** can now fully engage the engine-to-ring clutch **214** without a sudden shock. Controller **234** begins to increase its signal to the engine-to-ring clutch **214** to eliminate all clutch slippage and fully engage the engine-to-ring clutch **214**.

[0089] At time t=420, the engine **104** and ring gear **216** are fully engaged with no slippage. The engine **104** and motor **112** rotate at a constant speed, driving the rotor **118** at a constant speed as well.

[0090] At time t=462, the speeds of the rotor **118**, motor **112** and engine **104** have stabilized. The controller **234** begins increasing the signal applied to the pump (trace

300) causing the motor to slow down and stop, and then to begin accelerating on the opposite direction. While the motor **112** slows down, stops, and reverses direction, the rotor **118** again increases in speed (trace **306**).

Overview of the Gear Ratio Determination Process

[0091] **FIGURES 4**, **5**, and **6** are flow charts of the operation of controller **234** as it determines the gear ratio of gearbox **116**. This is a threefold process.

[0092] In the first stage, shown in **FIGURE 4**, controller **234** repeatedly calculates the motor/rotor speed ratio and the corresponding gear ratio of the gearbox fifty times in a row. Each time through it calculates which of the three gear ratios the gearbox is engaged in: first, second or third gear. It repeats this process at least twice, preferably fifty times. Controller **234** simultaneously calculates three sums that are stored in three variables: Counter[0], which indicates how many times controller **234** calculates first gear as the gear ratio; Counter[1], which indicates how many times controller **234** calculates second gear as the gear ratio; and Counter[2], which indicates how many times controller **234** calculates third gear as the gear ratio. In short, controller 234 sums the results of the gear ratio calculations, keeping a running count or sum for each of the three gear rations it determines. The speed ratio is the ratio of the motor speed (an input to the gearbox) and the rotor speed (an output from the gearbox).

[0093] The second stage, shown in **FIGURE 5**, selects between these three sums (i.e. selects between the first, second and third gear ratios) to determine which of these three gear ratios the gearbox is actually engaged in. Theoretically, all the calculated gear ratios should be the same, but due to clutch slippage, sensor errors and other effects, not all of the fifty gear ratio calculations may be the same. In this process of selecting between the gear ratios it has already summed, the controller **234** determines which of the three sums (i.e. Counter[0], Counter[1], or Counter[2]) exceeds a minimum value. In this case, the minimum value is 30 (i.e. controller **234** selected a gear ratio 30 times out of a possible 50 times). Clearly, if controller **234** calculated one of the three gear ratios at least 30 out of 50 total times, the sum corresponding to that gear ratio will

be greater than the sum corresponding to either of the other two gear ratios. Any gear ratio selected in this stage has a sum that is greater than the other sums. If none of the sums is greater than the threshold value of 30, then the first gear ratio determination process fails.

[0094] The third stage, shown in **FIGURE 6**, is performed when the first gear ratio determination process fails. In the third stage, the controller waits a predetermined time interval. After that time interval, controller **234** calculates the speed ratio and determines the gearbox gear ratio based on that calculation. This process is repeatedly performed over a second time interval. At the end of this interval, controller **234** saves the last gear ratio it successfully determined as the correct gear ratio. Controller **234** does not sum its choices and select between them as it does in the first and second stages of the process. The speed ratio that controller **234** calculates here is the engine-to-rotor speed ratio. If both processes to determine the speed range fail, the last known valid gear selection would be used.

Details of the Gear Ratio Determination process

[0095] In the discussion below, we refer to a counter or timer that is identified as "i". Variable "i" is automatically incremented every ten milliseconds when controller 234 executes the instructions below. Hence "i" always indicates the time in ten millisecond increments since the start of the rotor engagement and gear ratio determination processes.

[0096] Checking to see whether "i" equals 150, for example, is the same as testing whether 1.5 seconds have passed since the gear ratio determination process started.

[0097] Controller **234** starts the gear ratio determination process in block **400**. Controller **234** is configured to start this process every time the operator requests that the rotor be engaged and brought up to speed. This rotor engagement and acceleration process is shown in **FIGURE 3**. It begins at time i=0.

[0098] After starting at time i=0 (block **400**), controller **234** initializes several counters in block **402**. Counter[2] will increase by 1 whenever controller **234** estimates that the

gearbox **116** is in third gear. Counter[1] will increase by 1 whenever controller **234** estimates that the gearbox is in second gear. Counter[0] will increase by 1 whenever controller **234** estimates that gearbox **116** is in first gear.

[0099] Controller **234** then checks to see whether the rotor speed has stabilized and is ready to be checked (block **402**). The speed is stabilized when controller **234** has accelerated the rotor for 1.5 seconds (i.e. when "i" is equal to or greater than 150 in block **402**).

[00100] Once the time "i" is at least 150, the rotor is up to speed. Controller **234** then checks to make sure the first stage gear ratio determination is not complete by checking whether i<=199 (block **404**). If the first stage is not complete, controller **234** continues to block **506**.

[00101] In block **406**, controller **234** reads the motor speed sensor and the rotor speed sensor and calculates the speed ratio–the ratio of the two (block **406**). This speed ratio indicates the gear ratio of gearbox **116**.

[00102] In block **408**, controller **234** checks the speed ratio to see if it is within a range of 8 and 15. If it is, then controller **234** increments Counter[2], indicating that it has determined the gearbox to be in third gear. When gearbox **116** is in third gear, the actual speed ratio will be about 11. Rather than checking to see if the ratio is precisely 11 (as it should be if the gearbox is in third gear) the 8-15 range in block **406** accommodates for minor system errors.

[00103] If the speed ratio is not in this range (i.e. the gearbox **116** is not in third gear), controller **234** continues to block **410** and checks to see if the speed ratio is between 15 and 25. If it is, controller **234** increments Counter [1], indicating that it has determined the gearbox **116** to be in second gear. When gearbox **116** is in second gear, the actual speed ratio will be about 20. Rather than checking to see if the ratio is precisely 20 (as it should be if the gearbox is in second gear) the range of 15-25 in block **408** accommodates minor system errors.

[00104] If the speed ratio is not in this range (i.e. the gearbox **116** is not in second gear), controller **234** continues to block **412** and checks to see if the speed ratio is between 25 and 40. If it is, controller **234** increments Counter [0], indicating that it has

determined the gearbox **116** to be in first gear. When gearbox **116** is in first gear, the actual speed ratio will be about 32.5. Rather than checking to see if the ratio is precisely 32.5 (as it should be if the gearbox is in first gear) the 25-40 range in block **410** accommodates minor system errors.

[00105] If the speed ratio is not in any of the three ranges, as indicated by the "no" branch from block **412**, then an error has occurred and controller **234** does not increment Counter[0], Counter[1], or Counter[2].

[00106] Controller **234** proceeds to increment the time counter, "i" (block **420**), and returns to block **404**.

[00107] Controller **234** stays in the block **404-420** loop for 0.5 seconds (until i>199 in block **404**) calculating fifty successive speed ratios, one calculated every ten milliseconds. Controller **234** simultaneously characterizes each of the fifty as representing the gearbox gear ratio as first, second or third gear.

[00108] If all fifty values do not agree, there may be a sensor failure or intermittent fault of some kind. It is for this reason that the second stage of gear ratio determination, in which it determines (1) which gear ratio was calculated more times than any others (i.e. 30 times, all others being calculated 20 times or less), (2) which gear ratio was calculated the majority of the times (i.e. 30 times out of a total of 50 times), and (3) which gear ratio was calculated more than a predetermined number of times (i.e. 30 times). This process is shown in **FIGURE 5**.

[00109] In **FIGURE 5**, controller 234 proceeds to examine the 50 calculated gear ratios (the three sums, Counter[0], Counter[1] and Counter[2]) and to decide which of the three gear ratios is correct. This further processing occurs when the time counter reaches **200**.

[00110] When the time counter "i" reaches **200** and the 500 milliseconds of gear ratio calculations are finished, controller **234** will answer "no" to block **404**. It will then continue to tag "A" (**FIG. 5**) and execute block **502**. In block **502**, controller **234** checks to see if time counter i equals 200, which it does. Controller **234** continues to block **504** and sets the flag "gear_found" equal to 1.

[00111] Controller **234** then executes block **506**, checking Counter[0] to see if it is at

least 30. Counter[0] will be at least 30 if the gear ratio calculated in **FIG. 4** was indicated first gear 60% of the time (i.e. 30 out of the 50 times). If Counter[0] is at least 30, controller **234** proceeds to block **516** and sets ratio=1, indicating that gearbox **116** is in first gear.

[00112] On the other hand, if Counter[0] is not at least 30 in block **506**, controller **234** then executes block **508**, checking Counter[1] to see if it is at least 30. Counter[1] will be at least 30 if the gear ratio calculated in **FIG. 4** indicated second gear 60% of the time (i.e. 30 out of the 50 times). If Counter[1] is at least thirty, controller **234** proceeds to block **518** and sets ratio=2, indicating that gearbox **116** is in second gear.

[00113] Alternatively, if Counter[1] is not at least 30 in block **508**, controller **234** then executes block **510**, checking Counter[2] to see if it is at least 30. Counter[2] will be at least 30 if the calculated gear ratio in **FIG. 4** indicated third gear 60% of the time (i.e. 30 times out of the 50 times in **FIG. 4** that controller **234** checked). If Counter[2] is at least thirty, controller **234** proceeds to block **520** and sets ratio=3, indicating that gearbox **116** is in third gear.

[00114] If controller **234** determines the gear ratio was first, second or third gear, then processing stops--the gear ratio determination process is complete, per block **522**.

[00115] On the other hand, if no single gear ratio was calculated at least 60% of the time (30 times) in **FIG. 4**, then controller **234** sets the gear_found flag to false (i.e. "0") in block **512**, "i" is incremented (block **514**) and processing returns to block **502**.

[00116] Since "i" now equals 201, controller **234** will answer "no" in block **502** and continue processing at block **602** in FIG. 6.

[00117] In block **602**, controller **234** checks to see if the second phase of acceleration (**FIG. 3**) is complete—in other words, that the time count has reached i=420. Since i=201, controller **234** continues to block **604**, in which "i" is incremented, indicating the passages of another ten milliseconds. This process of incrementing time counter i every ten milliseconds (block **604**) continues until i=420--about 4.2 seconds into the rotor acceleration process of **FIG. 3**.

[00118] Controller **234** has now delayed until the rotor speed has stabilized with both the motor and the engine driving the rotor at a stable speed (see **FIG 3** and

accompanying description).

[00119] Once i=420 in block **602**, controller **234** continues to block **606**, in which it checks to see if the time counter has reached 462, or 4.62 seconds into rotor acceleration process. When the time counter i reaches 462, controller **234** halts the gear estimation process (block **608**).

[00120] While time counter i is between 420 (block **602**) and 462 (block **606**), however, controller **234** executes the program steps shown in blocks **610-624**.

[00121] In block **610**, controller **234** reads the engine speed sensor and the rotor speed sensor and saves the values. It then continues to block **612** where it examines the rotor speed (RS) to see if it is less than 0.152 times the engine speed (ES). In other words, to see if the engine-to-rotor speed ratio is less than 0.152.

[00122] For the particular embodiment illustrated herein, with the pump command at its negative maximum as shown in **FIG. 3** at time i=420, this ratio can only occur when gearbox **116** is in first gear. If RS is less than 0.152 times ES, then controller **234** continues to block **614**, where it sets ratio equal to 1, which indicates that gearbox **116** is in first gear.

[00123] If the answer to block **612** is "no", controller **234** continues to block **616**, where it checks to see if RS is between 0.152 times ES and 0.243 times ES. In other words, to see if the engine-to-rotor speed ratio is greater than or equal to 0.152 and less than 0.243. If the answer is "yes", controller **234** continues to block **618**, where it sets ratio equal to 2, which indicates that gearbox **116** is in second gear.

[00124] If the answer to block **616** is "no", controller **234** continues to block **620**, where it checks to see if RS is between 0.243 times ES and 0.58 times ES. Expressed differently, it checks to see if the engine-to-rotor speed ratio is greater than or equal to 0.243 and less than 0.58. If the answer is "yes", controller **234** continues to block **622**, where it sets ratio equal to 3, which indicates that gearbox **116** is in third gear.

[00125] If rotor speed RS meets none of the conditions of blocks **612**, **616**, and **620**, then it is deemed to bean erroneous or incorrect reading and "ratio" is not set, as indicated by the "no" path extending from block **620** to block **624**.

[00126] Having set "ratio" to either 1, 2, or 3 (or having not set "ratio" at all because

the three tests of blocks **612, 616, 620** failed to identify a proper gear ratio), controller **234** then increments "i" (in block **624**) and returns to block **606**, where it again checks to see if "i" has reached 462.

[00127] After looping through blocks **606-624** several times, incrementing "i" on each pass, controller **234** will eventually go to block **608** and stop. This terminates the gear ratio determination process. The gear ratio that controller **234** finally determines in **FIG. 6** is the last gear ratio selected in any of blocks **612, 616, 620**.

[00128] Given the specific mathematical model of the drive system, whenever the pump command is set to its extreme negative position (see **FIG. 3**, for time i=420 through time i=462), the tests of block **612, 616**, and **620** will identify the actual gear ratio of gearbox **116**. As in the case of blocks **408, 410** and **412**, the actual rotor-to-engine speed ratio is a fixed ingle value, and the ranges are provided to accommodate system errors such as clutch slippage or minor sensor flaws.

[00129] The particular constants used in blocks **408, 410, 412, 612, 616**, and **620** will depend upon the specific drive systems design. A vehicle having different gears with different sizes engaging in a different manner will have a different system model and use different constants.

[00130] From the discussion above, it should be clear that the combine has a control system that calculates gear ratios based upon rotor speed signals, engine speed signals and motor speed signals.

[00131] It should also be clear that the system provides two alternative processes for determining the gear ratio, including a primary process and a redundant, supplemental, or fall-back process.

[00132] It should be clear that these two processes use different sensor signals and therefore can compensate for sensor failure, particularly failure of speed sensors, and more particularly for failure of a motor speed sensor.

[00133] It should also be clear that the two processes are performed during two different periods when the combine rotor is initially started, that they are performed automatically, and that they are performed automatically in response at least to the operator's request to start the rotor moving.

[00134] From the foregoing, it will be observed that numerous modifications and variations can be effected without departing from the true spirit and scope of the novel concept of the present invention. It will be appreciated that the present disclosure is intended as an exemplification of the invention, and is not intended to limit the invention to the specific embodiment illustrated. The disclosure is intended to cover by the appended claims all such modifications as fall within the scope of the claims.